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## SUMMARY

Gear endurance tests and rolling-element fatigue tests were conducted on CBS 600 steel to investigate its possible use as a gear material. The results of these tests were compared to data for AISI 9310 material. The tests were conducted with one lot of gears manufactured from consumable-electrode vacuum-melted (CVM) AISI 9310 and one lot of gears manufactured from air-melt CBS 600. The gear pitch diameter was 8.89 centimeters (3.5 in.). Test conditions were a gear temperature of 350 K (170° F), a maximum Hertz stress of  $1.71 \times 10^9$  newtons per square meter (248 000 psi), and a speed of 10 000 rpm.

Bench-type rolling-element fatigue tests were conducted to compare both air-melt and CVM CBS 600 with CVM AISI 9310. Tests were conducted at ambient temperature with a bar specimen speed of 12 500 rpm and a maximum Hertz stress of  $3.83 \times 10^9$  newtons per square meter (700 000 psi).

The CBS 600 material exhibited pitting fatigue lives both in rolling-element specimens and in gears at least equivalent to that of AISI 9310. Tooth fracture failure occurred with the CBS 600 gears after overrunning a fatigue spall. No such failure mode occurred with the AISI 9310 gears. Tooth fractures were attributed to excessive carbon content in the case, excessive case depth, and a higher than normal core hardness.

## INTRODUCTION

There is a continuing demand for improved performance, reduced weight, and increased temperature in current and advanced helicopters, VSTOL aircraft, and geared-fan jet engines. AISI 9310 steel is the material used most frequently to manufacture gears for aircraft today. The material is a carburized steel with a soft core. Gears made from this material exhibit good endurance characteristics (refs. 1 and 2). However, because AISI 9310 loses much of its hardness at temperatures beyond 394 K (250° F) (ref. 3), its application to advanced aircraft systems may be limited. In addition, many current aircraft transmission systems may be required to operate for prolonged periods at high gear temperatures because of oil cooling limitations or oil system failure. As a result, if the temperature of an AISI 9310 gear can exceed its material temperature limitation, then the AISI 9310 material will have to be replaced with one having a higher temperature limitation.

Several carburizing-type steels have been developed for use in tapered-roller bearings (refs. 3 to 5) in the 478 to 589 K (400° to 600° F) range. Since these are case car-

burized steels with hard surfaces and softer, more tough cores, they may have possible application as gear materials. One of these materials is known as CBS 600 (ref. 4). The material maintains a suitable bearing hardness (Rockwell C 58) to 505 K (450<sup>0</sup> F) for long-term operation and to 589 K (600<sup>0</sup> F) for short-time operation (refs. 4 and 5). CBS 600 is a low alloy material that has good machinability and carburizes easily. Because of its hot hardness strength and carburizing quality, CBS 600 is promising for use as a gear material in advanced aircraft applications.

The objectives of the research reported herein were to (1) investigate CBS 600 steel for use as a gear material, (2) determine the endurance characteristics of CBS 600, and (3) compare the results with AISI 9310. To accomplish these objectives, tests were conducted with one lot of spur gears made from a single heat of air-melt CBS 600 material. For comparison purposes, one lot of spur gears manufactured from a single heat of consumable-electrode vacuum-melted (CVM) AISI 9310 was also tested. The gear pitch diameter was 8.89 centimeters (3.5 in.). Test conditions include a gear temperature of 350 K (170<sup>0</sup> F), a maximum Hertz stress of  $1.71 \times 10^9$  newtons per square meter ( $\text{N/m}^2$ ) (248 000 psi), and a shaft speed of 10 000 rpm. Bench-type rolling-element fatigue tests were conducted to compare both air-melt and CVM CBS 600 with CVM AISI 9310. Tests were conducted at ambient temperature with a bar specimen speed of 12 500 rpm and a maximum Hertz stress of  $4.83 \times 10^9 \text{ N/m}^2$  (700 000 psi).

## APPARATUS, SPECIMENS, AND PROCEDURE

### Rolling-Element Fatigue Tests

Rolling-contact (RC) fatigue tester. - The rolling-contact (RC) fatigue tester is shown in figure 1. A cylindrical test bar is mounted in the precision chuck. The drive means attached to the chuck drives the bar which in turn drives two idler disks. The load is applied by closing the disks against the test bar using a micrometer-threaded turnbuckle and a calibrated load cell. Lubrication is supplied by a drip feed system using a needle valve to control the flow rate. Several test runs can be made on one test bar by moving the bar position in the axial direction relative to disk contacts. The test bar is rotated at 12 500 rpm and received 25 000 stress cycles per minute. The maximum Hertz stress was  $483 \times 10^9 \text{ N/m}^2$  (700 000 psi).

Test bar specimens. - The 7.62-centimeter- (3-in.-) long cylindrical test bars for fatigue tests were fabricated from both air-melt and CVM CBS 600 and CVM AISI 9310. The contacting disks were machined from CVM AISI M-50 steel and were through-hardened to Rockwell C 63±1. The test bars were ground to a diameter of 0.95 centimeter (0.375 in.) with a surface finish of 0.13 to 0.2 micrometer (5 to 8  $\mu\text{in.}$ ) CLA.

Similarly, the disks were ground to a disk diameter of 19 centimeters (7.5 in.) and a crown radius of 0.635 centimeter (0.25 in.). The surface finish of the disks was the same as that of the test bars.

Test materials. - Three lots of CVM CBS 600, one lot of air-melt CBS 600, and one lot of CVM AISI 9310 test bars were tested. The chemical compositions of the materials are given in table I. Lot A bars of air-melt CBS 600 were from the same material heat as the air-melt CBS 600 test gears. Lots B, C, and D bars were from a single CVM CBS 600 material heat. The bars were carburized and heat treated according to the specifications in table II. Resulting hardness, core depths, retained austenite, and grain size are shown in table III.

Test lubricant. - The RC bar specimens of both materials used in the rolling-element fatigue tests were lubricated with a diester-type lubricant, meeting the MIL-L-7808 specification. The fluid comprised a mixture of two base stocks, a diester plus a (trimethylol propane) polyester. The additives in this fluid included antioxidants, load-carrying additives, metal passivators, a hydrolytic stability additive, and a silicone antifoam additive. The types and levels of the additives were proprietary. The lubricant properties are given in table IV.

Test procedure. - Fatigue testing was performed in the RC rig. The test bar was installed and the disks were brought against the bar using the turnbuckle. The load applied was sufficient to allow the bar to drive the contacting disks, and the bar was accelerated to the 12 500 rpm test speed.

When the disks and test bar were in thermal equilibrium at a bar temperature of approximately 305 K (90° F), the full load was applied to give the test bar a stress of  $4.83 \times 10^9$  N/m<sup>2</sup> (700 000 psi). When a fatigue failure occurred, the rig and related instrumentation were automatically shut down by a vibration detection system. The axial position of the test bar in the drive chuck was changed to use a new running track before testing was resumed.

## Gear Endurance Tests

Gear test apparatus. - The gear fatigue tests were performed in the NASA Lewis Research Center's gear test apparatus (fig. 2). This test rig uses the four-square principle of applying the test gear load so that the input drive only needs to overcome the frictional losses in the system.

A schematic of the test rig is shown in figure 2(b). Oil pressure and leakage flow are supplied to the load vanes through a shaft seal. As the oil pressure is increased on the load vanes inside the slave gear, torque is applied to the shaft. This torque is transmitted through the test gears back to the slave gear where an equal but opposite torque is maintained by the oil pressure. This torque on the test gears, which depends

on the hydraulic pressure applied to the load vanes, loads the gear teeth to the desired stress level. The two identical test gears can be started under no load, and the load can be applied gradually, without changing the running track on the gear teeth.

Separate lubrication systems are provided for the test gears and the main gearbox. The two lubricant systems are separated at the gearbox shafts by pressurized labyrinth seals. Nitrogen is the seal gas. The test gear lubricant is filtered through a 5-micrometer nominal fiberglass filter. The test lubricant can be heated electrically with an immersion heater. The skin temperature of the heater is controlled to prevent overheating the test lubricant.

A vibration transducer mounted on the gearbox is used to automatically shut off the test rig when a gear-surface fatigue occurs. The gearbox is also automatically shut off if there is a loss of oil flow to either the main gearbox or the test gears, if the test gear oil overheats, or if there is a loss of seal gas pressurization.

The belt-driven test rig can be operated at several fixed speeds by changing pulleys. The operating speed for the tests reported herein was 10 000 rpm.

Test gears. - Dimensions for the test gears are given in table V. All gears have a nominal surface finish on the tooth face of 0.406 micrometer (16  $\mu$ in.) rms and a standard 20<sup>0</sup> involute profile with tip relief. Tip relief was 0.0013 centimeter (0.0005 in.) starting at the highest point of single tooth contact.

Test materials. - The test gears were manufactured from consumable-electrode vacuum-melted (CVM) AISI 9310 and air-melted CBS 600 steel from the same heat of material as lot A of the RC bars. The nominal chemical compositions of these materials are given in table I. Both sets of gears were case carburized and heat treated in accordance with the heat treatment schedule of table VI. Figure 3 is a photomicrograph of an etched and polished gear tooth surface showing the case microstructure of the AISI 9310 material. This material had a case hardness of Rockwell C 58 and a case depth of 0.97 millimeter (0.038 in.). The nominal core hardness was Rockwell C 40.

Figure 4 is a photomicrograph of an etched and polished gear tooth surface that shows the case microstructure of the CBS 600 material. The gears made of this material had a nominal case hardness of Rockwell C 61 and a case depth of 1.47 millimeters (0.058 in.). The nominal core hardness was Rockwell C 45.

Test lubricant. - All the gears were lubricated with a single batch of synthetic paraffinic oil. The physical properties of this lubricant are summarized in table IV. Five percent of an extreme pressure additive, designated Lubrizol 5002 (partial chemical analysis given in table IV), was added to the lubricant.

Test procedure. - After the test gears were cleaned to remove the preservative, they were assembled on the test rig. The test gears were run in an offset condition with a 0.30-centimeter (0.120-in.) tooth-surface overlap to give a load surface on the gear face of 0.28 centimeter (0.110 in.), thereby allowing for edge radius of the gear teeth.

If both faces of the gears were tested, four fatigue tests could be run for each set of gears. All tests were run-in at a load of 1225 N/cm (700 lb/in) for 1 hour. The load was then increased to 5784 N/cm (3305 lb/in) which gives a  $1.71 \times 10^9$ -N/m<sup>2</sup> (248 000-psi) pitch-line maximum Hertz stress. At the pitch-line load the tooth bending stress was  $0.21 \times 10^9$  N/m<sup>2</sup> (30 000 psi) if plain bending is assumed. However, because there is an offset load there is an additional stress imposed on the tooth bending stress. Combining the bending and torsional moments gives a maximum stress of  $0.26$  N/m<sup>2</sup> (37 000 psi). This bending stress does not include the effects of tip relief which would also increase the bending stress.

Operating the test gears at 10 000 rpm gave a pitch-line velocity of 46.55 meters per second (9163 ft/min). Lubricant was supplied to the inlet mesh at 800 cubic centimeters per minute at  $319 \pm 6$  K ( $116^{\circ} \pm 10^{\circ}$  F). The lubricant outlet temperature was nearly constant at  $350 \pm 3$  K ( $170^{\circ} \pm 5^{\circ}$  F). The tests ran continuously (24 hr/day) until they were automatically shut down by the vibration detection transducer, located on the gearbox adjacent to the test gears. The lubricant circulated through a 5-micrometer fiberglass filter to remove wear particles. For each test, 3800 cubic centimeters (1 gal) of lubricant were used. At the end of each test, the lubricant and filter element were discarded. Inlet and outlet oil temperatures were continuously recorded on a strip-chart recorder.

The pitch-line elastohydrodynamic (EHD) film thickness was calculated by the method of reference 6. It was assumed, for this film thickness calculation, that the gear temperature at the pitch line was equal to the outlet oil temperature and that the inlet oil temperature to the contact zone was equal to the gear temperature, even though the oil inlet temperature was considerably lower. It is possible that the gear surface temperature was even higher than the oil outlet temperature, especially at the end points of sliding contact. The EHD film thickness for these conditions was computed to be 0.33 micrometer (13  $\mu$ in.), which gave an initial ratio of film thickness to composite surface roughness ( $h/\sigma$ ) of 0.55 at the  $1.71 \times 10^9$ -N/m<sup>2</sup> (248 000-psi) pitch-line maximum Hertz stress.

## RESULTS AND DISCUSSION

### Rolling-Element Fatigue

Test bars of consumable-electrode vacuum-melted (CVM) CBS 600, air-melted CBS 600, and CVM AISI 9310 were tested in the rolling-contact (RC) fatigue tester. The CBS 600 bars represented four heat treatment procedures. The bars were tested at a maximum Hertz stress of  $4.83 \times 10^9$  N/m<sup>2</sup> (700 000 psi) and a bar speed of 12 500 rpm. The tests were run at ambient temperature (no external heat source) with a MIL-L-7808

lubricant. The results of these tests are shown in the Weibull plots of figures 5 and 6 and are summarized in table VII and figure 7. These data were analyzed according to the methods of reference 7. The spalling fatigue failure for CBS 600 shown in figure 8 is typical of both materials.

The lot A test bars, from the same air-melted heat of material as the test gears, show a 10-percent life less than half that of the baseline CVM AISI 9310. Sectioning these test bars showed that the metallurgical structure was nonuniform and not normal for CBS 600. The structure had a larger grain size in the core and a preferential etching in the case with both nital and picral etching. This abnormal structure (shown in fig. 9) should be compared with the normal microstructure of CBS 600 (shown in fig. 10), since it was typical of the other three lots regardless of the heat treatment used. As shown in table III, lot A bars had a very high retained austenite and higher core hardness as well as the other abnormalities which indicate some deviations had occurred from the desired and specified heat treatment.

The three other lots of CVM CBS 600 were fabricated from a different heat of material and heat treated with these significant variations:

- (1) Lot C was essentially the same as lot A except for the preheat cycle.
- (2) Lot D included a deep freeze cycle.
- (3) Lot B was tempered at a lower temperature.

As shown in table III, these heat treatment variations produced little variation in the measurable case and core characteristics. Likewise, no significant differences were seen in the rolling-element fatigue lives shown in table VII.

The three CVM lots of CBS 600 gave lives exceeding the air-melted lot A as expected. Probably the abnormal microstructure of lot A was partly responsible for its relatively poor life. The more normal CBS 600 microstructure of lots B, C, and D gave lives equivalent to that of the baseline AISI 9310.

The confidence numbers for these data are given in table VII. The confidence number indicates the percentage of time the AISI 9310 will have a 10-percent life either greater than or less than that with a given lot of CBS 600. It was determined, by using the methods of reference 7, that there is no significant difference in the rolling-element fatigue life between AISI 9310 and CBS 600 for the test conditions reported.

### Gear Endurance

Two groups of gears, one made from CVM AISI 9310 and the other from air-melt CBS 600, were run in pairs until failure or 500 hours, whichever occurred first. Twenty (20) tests were conducted with the CBS 600 gear material on five sets of gears. Thirty (30) tests were conducted with the AISI 9310 gear material on eight sets of gears. Those tests which completed 500 hours without failure were treated as suspended tests.



Tests results were analyzed by considering each pair of gears as a system for each material.

Pitting fatigue results for the gears made from the CVM AISI 9310 material are shown in figure 11(a). These data were analyzed by the method of reference 7. The 10-percent and 50-percent lives were  $24 \times 10^6$  and  $54 \times 10^6$  stress cycles (40 and 90 hr), respectively. The failure index (i.e., the number of fatigue failures out of the number of sets tested) was 30 of 30. A typical fatigue spall that occurs near the pitch-line is shown in figure 12. This spall is similar to those observed in the rolling-element fatigue tests shown in figure 8. The pitch-line pitting is the result of high subsurface shearing stress which develops subsurface cracks. The subsurface originating cracks propagate into a crack network which results in a fatigue spall that is slightly below the pitch-line where the sliding condition is more severe.

Pitting fatigue results for the gears systems made from the CBS 600 material are shown in figure 11(b). The failure index was 2 out of 20. Eighteen (18) tests were suspended after 500 hours of test time. Since only two failures occurred, the life estimate for these tests was determined by assuming the same Weibull slope that was determined for the AISI 9310 data and then by drawing the line through the earliest failure point. The estimated 10-percent and 50-percent lives determined in this manner were  $180 \times 10^6$  and  $380 \times 10^6$  stress cycles (300 and 633 hr), respectively.

A statistical comparison was made of the differences in the gear tooth pitting life of the CVM AISI 9310 and air-melt CBS 600. The CBS 600 achieved a life at least 7.5 times that of AISI 9310. The confidence number for the difference in life was 99 percent, which is statistically significant. Based on the rolling-element fatigue tests reported herein, these gear test results would not have been predicted.

The major difference which could affect surface fatigue between the AISI 9310 material used for the rolling-element fatigue (RC bar) specimens and for the gears was their respective case hardness. For both the CBS 600 and AISI 9310, the rolling-element (RC bar) specimen nominal case hardness was Rockwell C 61. For the AISI 9310 gears, which were heat treated by a separate vendor, the normal gear case hardness was Rockwell C 58. The case hardness of the CBS 600 gears was Rockwell C 61. It is commonly accepted that component hardness affects the pitting fatigue life of a rolling-element system (ref. 8). Hence, it would be expected that the CBS 600 gears would have a longer life than the AISI 9310 gears. However, based on hardness alone, the difference in life would only be expected to be 20 to 30 percent (ref. 8) and not the 650 percent reported herein. Suffice it to say, the CBS 600 material exhibits a pitting fatigue life at least equivalent to AISI 9310.

One of the fatigue spalls on the CBS 600 gears is shown in figure 13(a). A cross section of this fatigue spall is shown in figure 13(b). The two gears with pitting failures were run for 6 hours after spalling had occurred. A single tooth bending fracture oc-

curred on each of the gears as a result of the overrun. A fractured tooth is shown in figure 14. AISI 9310 gears that were overrun did not fracture.

Reference 4 reports good fracture toughness for the CBS 600 material. There are three factors which may have contributed to tooth fracture after pitting occurred on the gear teeth. First, the resultant core hardness of Rockwell C 45 is excessive for the CBS 600 and therefore makes the material more brittle. Second, the case grain structure has large carbides from a slight amount of excess carbon (fig. 4); this condition would tend to promote bending-type fatigue failure. Third, there was an excessive case depth of 1.47 millimeters (0.058 in.) instead of the desired 0.76 millimeter (0.030 in.). All of these factors can and should be controlled. However, lower amounts of carbon, a lower core hardness, and a lower case depth may not by themselves assure an absence of bending failure when accompanied by surface pitting. Additional research must be undertaken to assure that tooth fracture can be eliminated with reasonable heat-treat procedures.

## SUMMARY OF RESULTS

Gear endurance tests and rolling-element fatigue tests were conducted to investigate CBS 600 steel for use as a gear material, to determine the endurance characteristics of CBS 600, and to compare the results with data for the AISI 9310 material. Tests were conducted with one lot of gears manufactured from consumable-electrode vacuum-melted (CVM) AISI 9310 and one lot of gears manufactured from air-melt CBS 600. The gear pitch diameter was 8.89 centimeters (3.5 in.). Test conditions were a gear temperature of 350 K (170<sup>0</sup> F), a maximum Hertz stress of  $1.71 \times 10^9$  N/m<sup>2</sup> (248 000 psi), and a speed of 10 000 rpm. Bench-type rolling-element fatigue tests were conducted to compare both air-melt and CVM CBS 600 with CVM AISI 9310. Tests were conducted at ambient temperature with a bar specimen speed of 12 500 rpm and a maximum Hertz stress of  $4.83 \times 10^9$  N/m<sup>2</sup> (700 000 psi). The following results were obtained:

1. The CBS 600 material exhibited pitting fatigue lives both in rolling-element specimens and in gears at least equivalent to that of AISI 9310.
2. Tooth fracture failures occurred with the CBS 600 gears overrunning a fatigue spall. No such failure mode occurred with AISI 9310 gears. Excessive carbon content in the case and excessive case depth and core hardness were thought to be the causes of the tooth fractures.

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Cleveland, Ohio, September 12, 1978,

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TABLE I. - NOMINAL CHEMICAL COMPOSITION OF MATERIALS BY  
PERCENT WEIGHT

Material	Element								
	C	Mn	Si	Ni	Cr	Mo	Cu	P	S
	Composition, wt %								
AISI 9310	0.10	0.63	0.27	3.22	1.21	0.12	0.13	0.005	0.005
CBS 600	.19	.61	1.05	.18	1.50	.94	----	.007	.014

TABLE II. - HEAT TREATMENT OF THE ROLLING-CONTACT TEST MATERIALS

Heat treatment	AISI 9310	CBS 600			
		Lot B (CVM)	Lot C (CVM)	Lot D (CVM)	Lot A (air melt)
Preheat	-----	-----	-----	-----	593° C (1100° F) for 2 hr
Carburize	941° C/698° C (1725° F/1775° F) for 12 hr	941° C/968° C (1725° F/1775° F) for 13 hr, oil quench	Same as lot B	Same as lot B	927° C (1700° F), oil quench
Temper	593° C (1100° F) for 10 hr, air cool	621° C (1150° F) for 4 hr, air cool	Same as lot B	Same as lot B	593° C/649° C (1100° F/1200° F) for 4 hr
Austenitize	857° C (1575° F) for 20 min, oil quench	829° C/843° C (1525° F/1550° F) in salt for 30 min, oil quench	Same as lot B	Same as lot B	829° C/843° C (1525° F/1550° F) for 25 min, oil quench
Deep freeze	-73° C (-100° F) for 3 hr	-----	-----	-73° C (-100° F) for 1 hr	-----
Temper	182° C (360° F) for 1 hr	182° C (360° F) for 2+2 hr	316° C (600° F) for 2+2 hr	Same as lot C	316° C (600° F) for 2+2 hr

TABLE III. - METALLURGICAL CASE AND CORE CHARACTERISTICS OF

## ROLLING-CONTACT TEST BARS

Material	Test lot (melt)	Effective <sup>a</sup> case depth, mm (in.)	Case hardness, Rockwell C	Case retained austenite, vol. %	Core	
					Hardness, Rockwell C	Grain size (ASTM number)
CBS 600	A (air melt)	0.76 (0.030)	62.9	22.8	41.0	6-7
	B (CVM)	.84 (.033)	61.7	4.3	↓	7-8
	C (CVM)	.84 (.033)	60.3	3.4		7-8
	D (CVM)	.76 (.030)	61.6	2.1		7-8
AISI 9310	----- (CVM)	.84 (.033)	61.4	11.2	38.0	---

<sup>a</sup>Depth below surface at which Rockwell C 50 occurs.

TABLE IV. - LUBRICANT PROPERTIES

Property	Synthetic paraffinic oil plus additives <sup>b</sup>	Diester plus TMP <sup>a</sup> polyester plus additives <sup>c</sup>
Kinematic viscosity, cm <sup>2</sup> /sec (cs) at:		
244 K (-20° F)	2500×10 <sup>-2</sup> (2500)	580×10 <sup>-2</sup> (580)
311 K (100° F)	31.6×10 <sup>-2</sup> (31.6)	14.8×10 <sup>-2</sup> (14.8)
372 K (210° F)	5.7×10 <sup>-2</sup> (5.7)	3.7×10 <sup>-2</sup> (3.7)
477 K (400° F)	2.0×10 <sup>-2</sup> (2.0)	1.2×10 <sup>-2</sup> (1.2)
Flash point, K (°F)	508 (455)	491 (425)
Fire point, K (°F)	533 (500)	527 (490)
Pour point, K (°F)	219 (-65)	213 (-75)
Specific gravity	0.8285	0.950
Vapor pressure at 311 K (100° F), mm Hg (or torr)	0.1	10 <sup>-5</sup>
Specific heat at 311 K (100° F), J/(kg)(K) (Btu/(lb)(°F))	676 (0.523)	608 (0.470)

<sup>a</sup>Trimethylol propane.

<sup>b</sup>Additive, Lubrizol 5002 (5 percent volume): phosphorus, 0.03 percent volume; sulfur, 0.93 percent volume.

<sup>c</sup>Additive content is proprietary to the manufacture.

TABLE V. - SPUR GEAR DATA

[Gear tolerance per ASMA class 12.]

Number of teeth . . . . .	28
Diametral pitch . . . . .	8
Circular pitch, cm (in.) . . . . .	0.9975 (0.3927)
Whole depth, cm (in.) . . . . .	0.762 (0.300)
Addendum, cm (in.) . . . . .	0.318 (0.125)
Chordal tooth thickness reference, cm (in.) . . . . .	0.485 (0.191)
Pressure angle, deg . . . . .	20
Pitch diameter, cm (in.) . . . . .	8.890 (3.500)
Outside diameter, cm (in.) . . . . .	9.525 (3.750)
Root fillet, cm (in.) . . . . .	0.102 to 0.152 (0.04 to 0.06)
Measurement over pins, cm (in.) . . . . .	9.603 to 9.630 (3.7807 to 3.7915)
Pin diameter, cm (in.) . . . . .	0.549 (0.216)
Backlash reference, cm (in.) . . . . .	0.0254 (0.010)
Tip relief, cm (in.) . . . . .	0.001 to 0.0015 (0.0004 to 0.0006)

TABLE VI. - HEAT TREATMENT FOR AISI 9310 AND CBS 600 GEARS

Step	Process	AISI 9310			CBS 600		
		Temperature		Time, hr	Temperature		Time, hr
		K	°F		K	°F	
1	Preheat in air	----	----	-----	866	1100	2
2	Carburize	1172	1650	8	1200	1700	8
3	Air cool to room temperature	----	----	-----	----	----	-----
4	Copper plate all over	----	----	-----	----	----	-----
5	Reheat	922	1200	2.5	894	1150	4
6	Air cool to room temperature	----	----	-----	----	----	-----
7	Austenitize	1117	1550	2.5	1117	1550	0.5
8	Oil quench	----	----	-----	----	----	-----
9	Subzero cool	180	-120	3.5	----	----	-----
10	Double temper	450	350	2 each	589	600	2 each
11	Finish grind	----	----	-----	----	----	-----
12	Stress relieve	450	350	2	589	600	2

TABLE VII. - FATIGUE RESULTS WITH ROLLING-CONTACT TEST BARS  
OF CBS 600 AND AISI 9310

Material	Test lot (melt)	10-percent life, cycles	50-percent life, cycles	Slope	Failure index <sup>a</sup>	Confidence number, percent <sup>b</sup>
CBS 600	A (air melt)	$1.9 \times 10^6$	$7.3 \times 10^6$	1.4	10/10	83
	B (CVM)	5.2	11.8	2.3	8/10	60
	C (CVM)	5.8	11.0	3.0	10/10	70
	D (CVM)	3.8	9.6	2.0	10/10	55
AISI 9310	----- (CVM)	4.2	9.4	2.3	10/10	--

<sup>a</sup>Indicates numbers of failures out of total number of tests.

<sup>b</sup>Probability, expressed as a percentage, that the 10-percent life with the baseline AISI 9310 bars is either less than, or greater than, the particular lot of CBS 600 bars being considered, as the case may be.

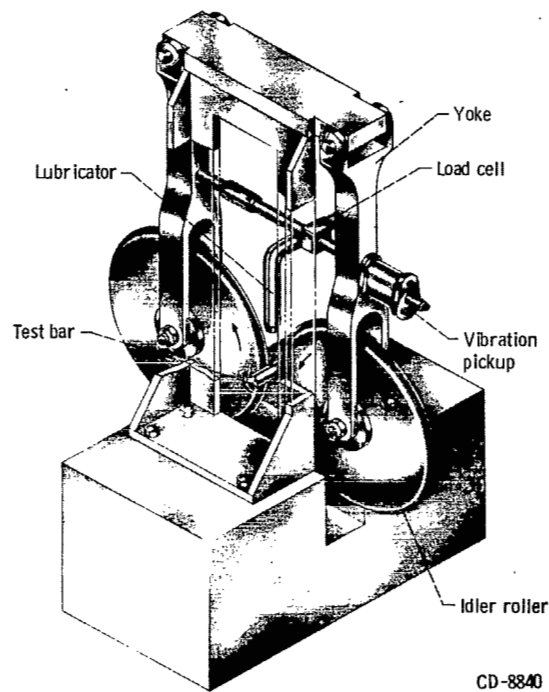
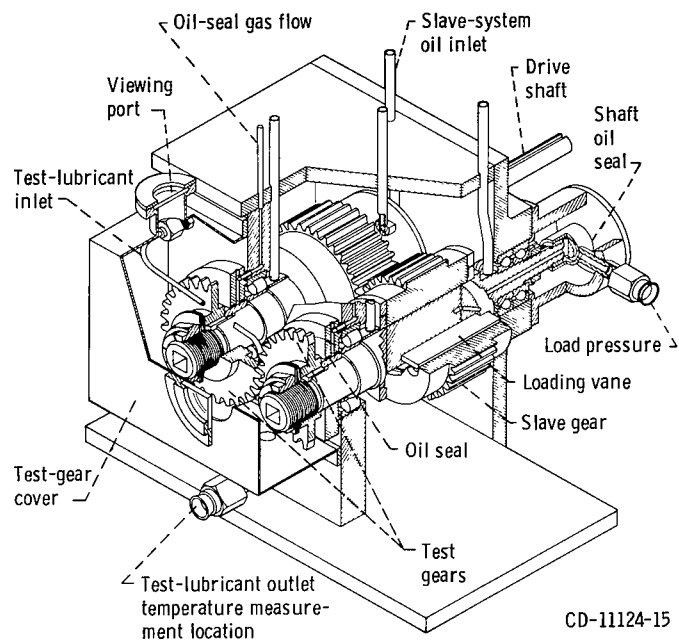
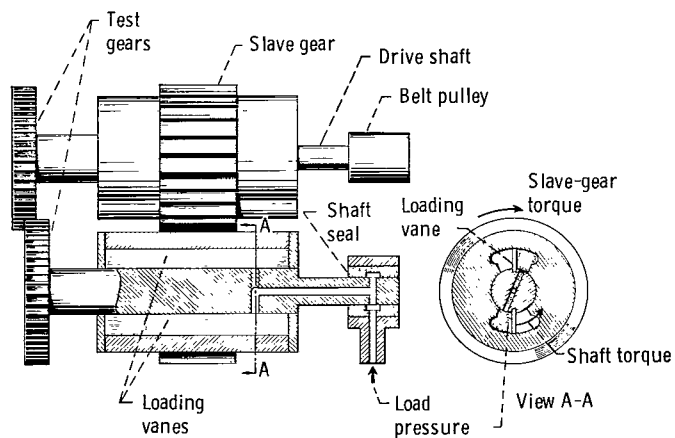


Figure 1. - Rolling-contact (RC) fatigue tester.



(a) Cutaway view.



(b) Schematic diagram.

Figure 2. - NASA Lewis Research Center's gear fatigue test apparatus.



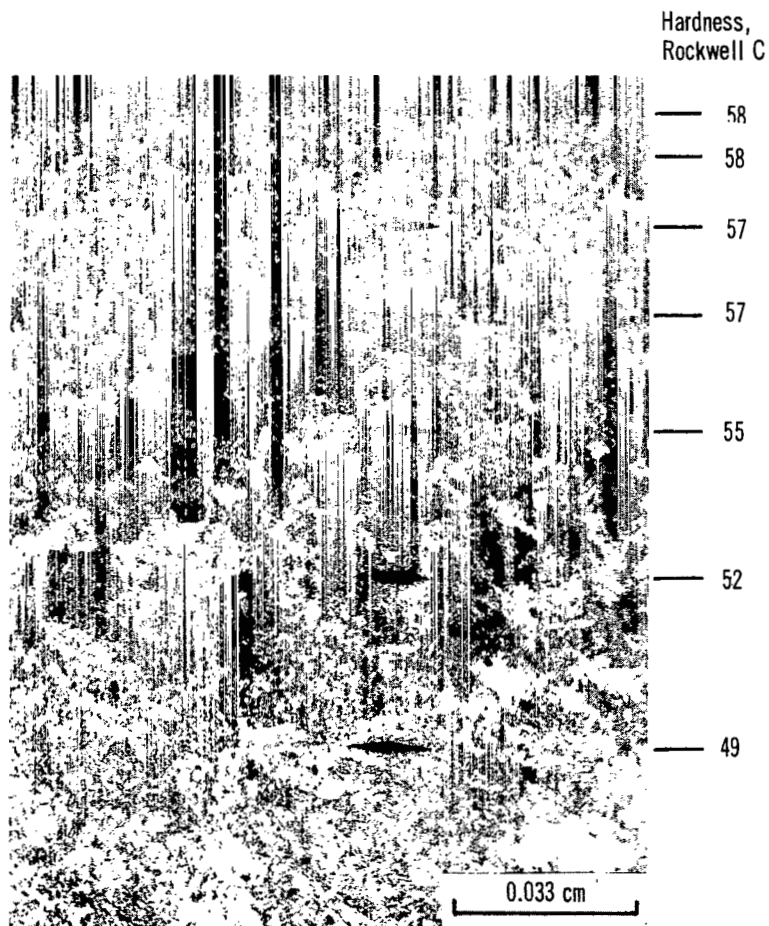


Figure 3. - Photomicrograph of case structure of CVM AISI 9310 showing high grain martensitic structure of case.

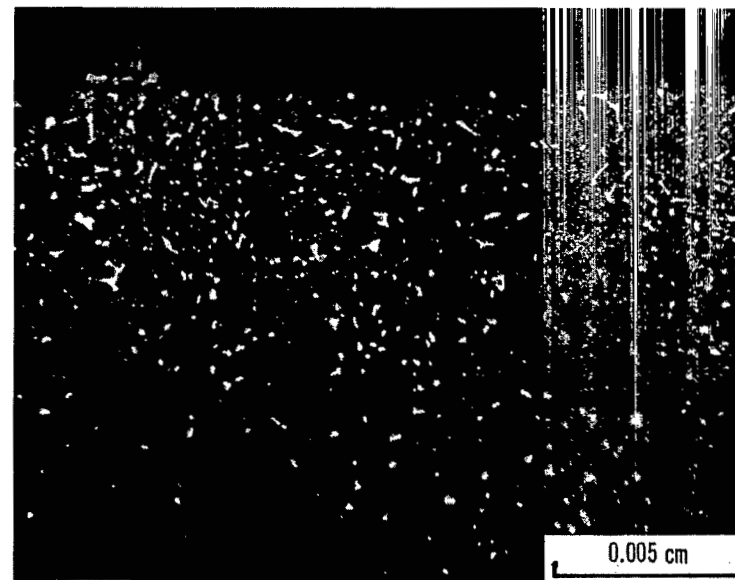


Figure 4. - Photomicrograph of case structure of CBS 600 showing large carbides resulting from excessive carbon.

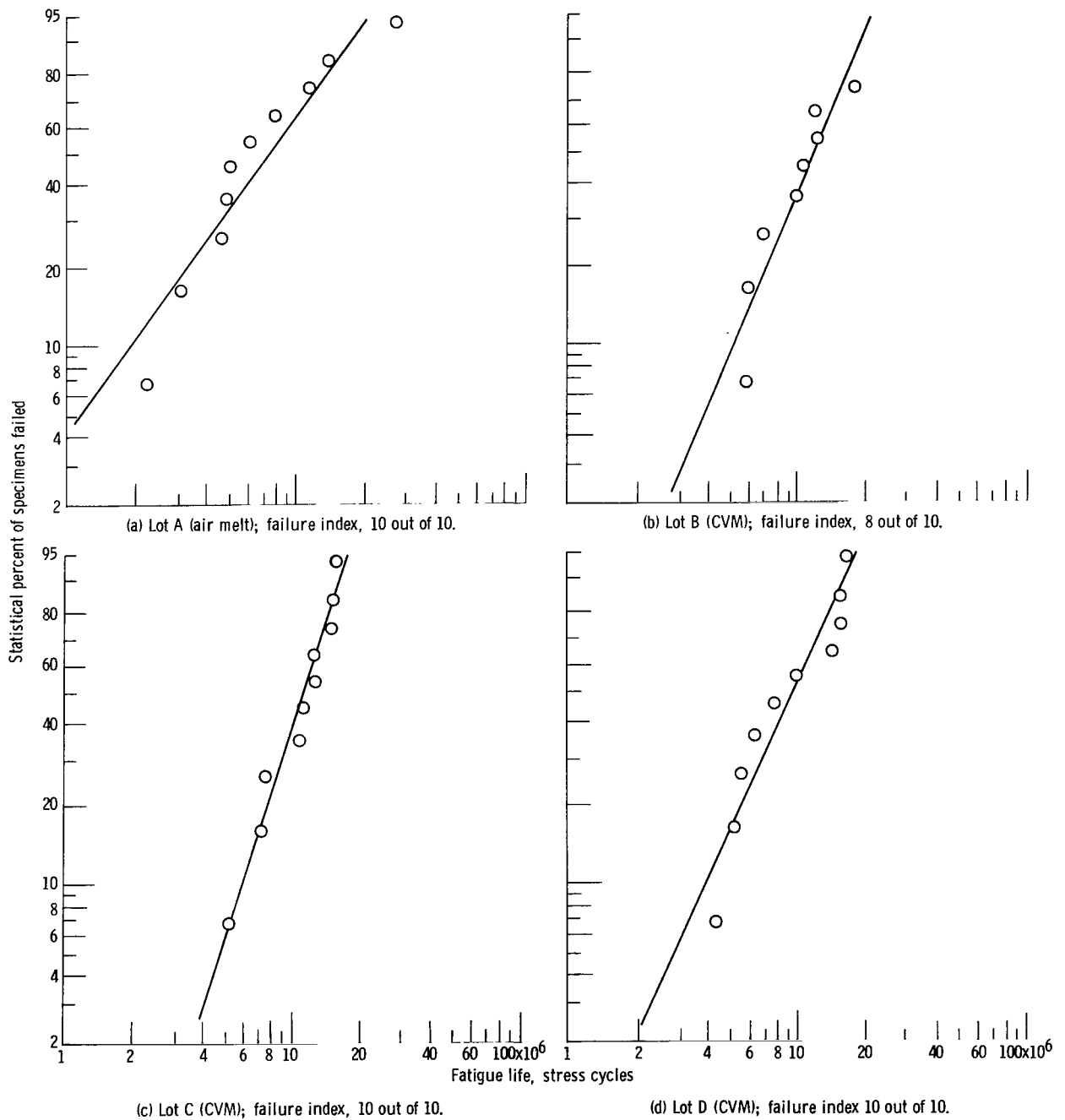


Figure 5. - Rolling-element fatigue life of CBS-600 test bars in rolling-contact fatigue tester. Maximum Hertz stress,  $4.83 \times 10^9$  newtons per square meter (700 000 psi); bar speed, 12 500 rpm; bar temperature, ambient; lubricant, MIL-L-7808.

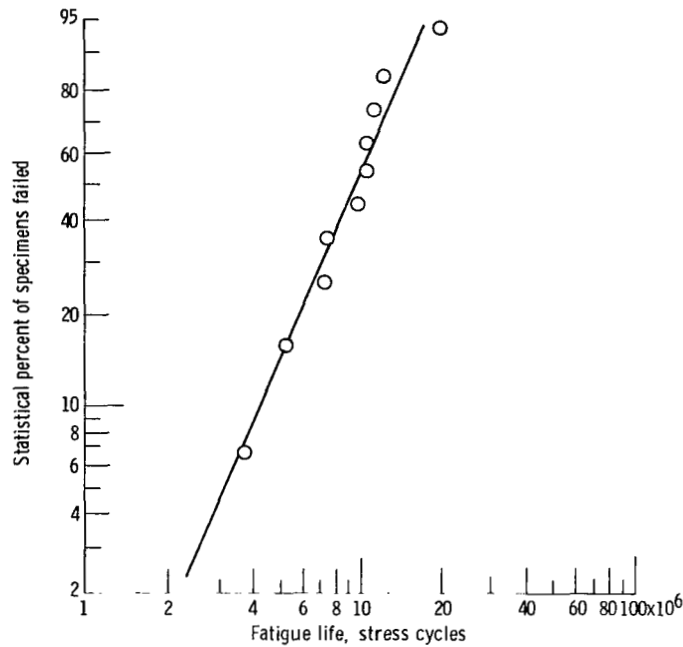


Figure 6. - Rolling-element fatigue life of CVM AISI 9310 test bars in rolling-contact fatigue tester. Maximum Hertz stress,  $4.83 \times 10^9$  newtons per square meter (700 000 psi); bar specimen speed, 12 500 rpm; bar specimen temperature, ambient; lubricant, MIL-L-7808.

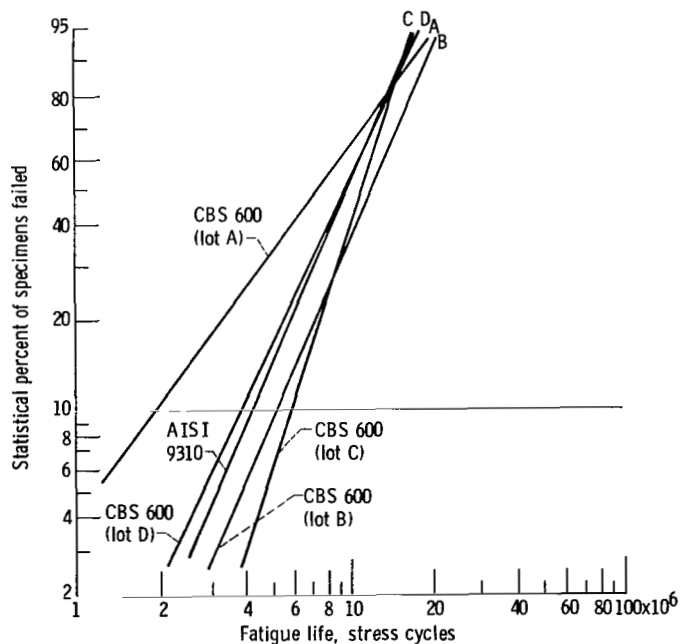


Figure 7. - Summary of rolling-element fatigue life data with CBS 600 and CVM AISI 9310 in rolling-contact fatigue tester.

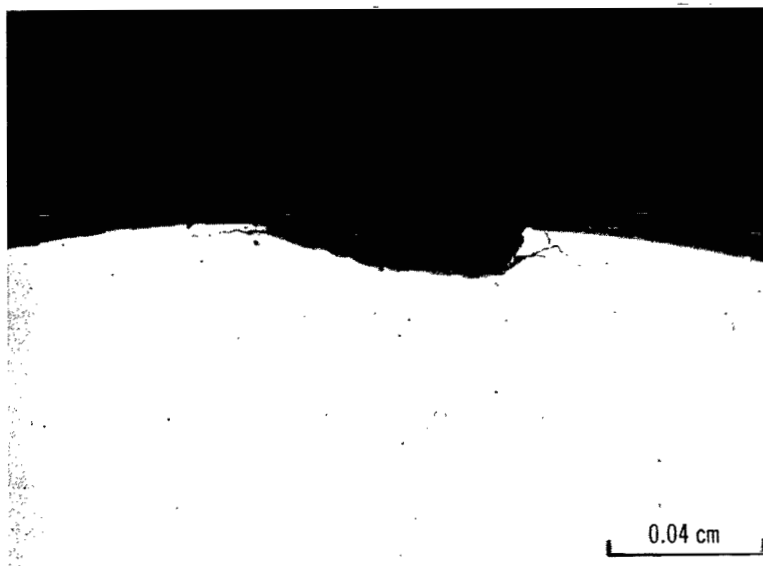
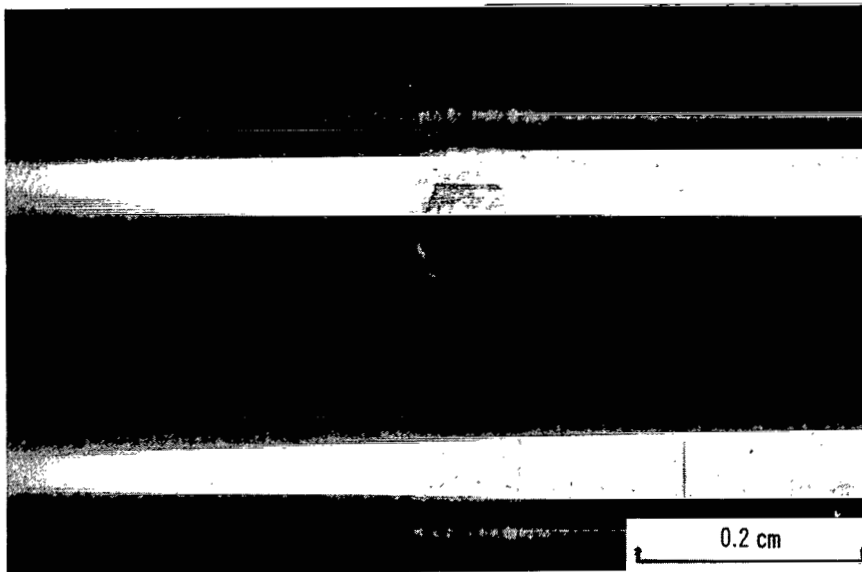
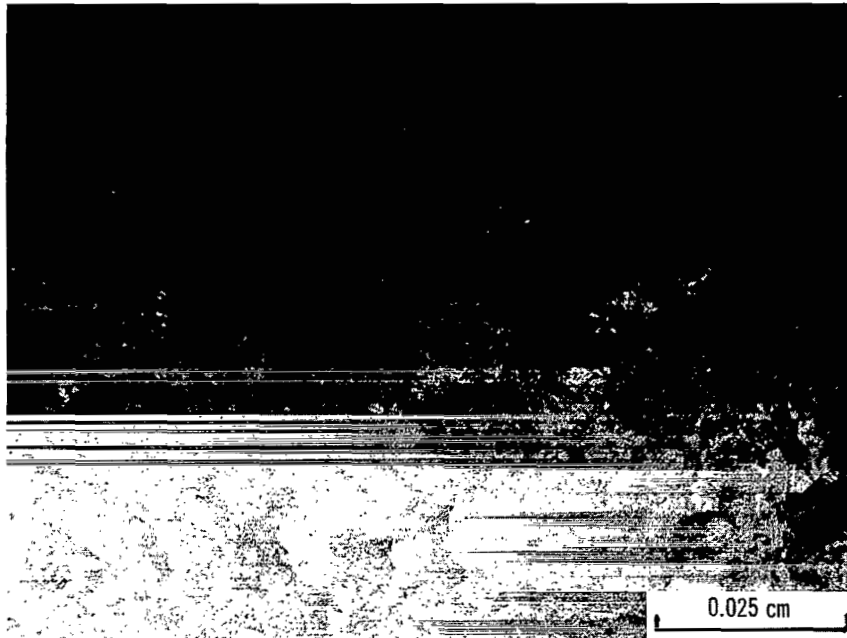
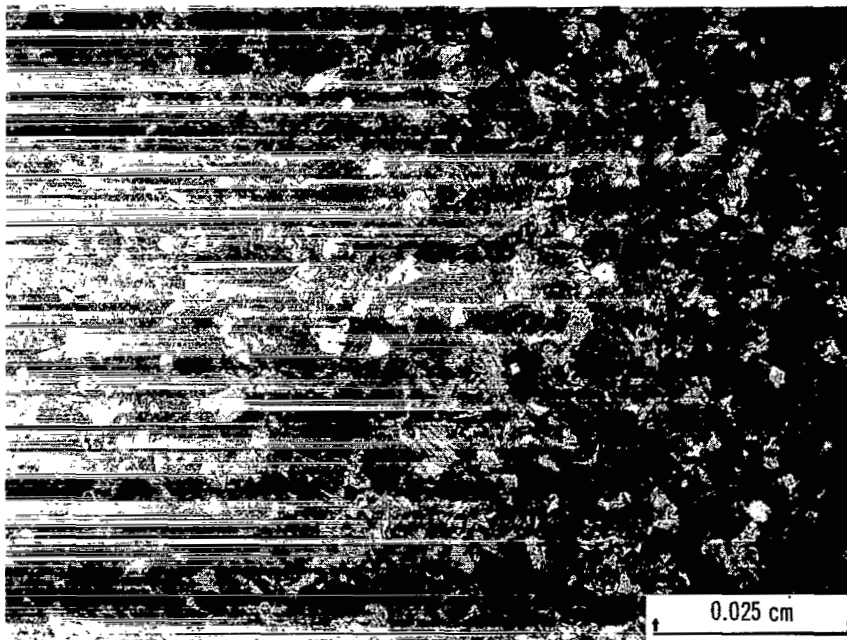


Figure 8. - Typical rolling-element fatigue failure in CBS 600.

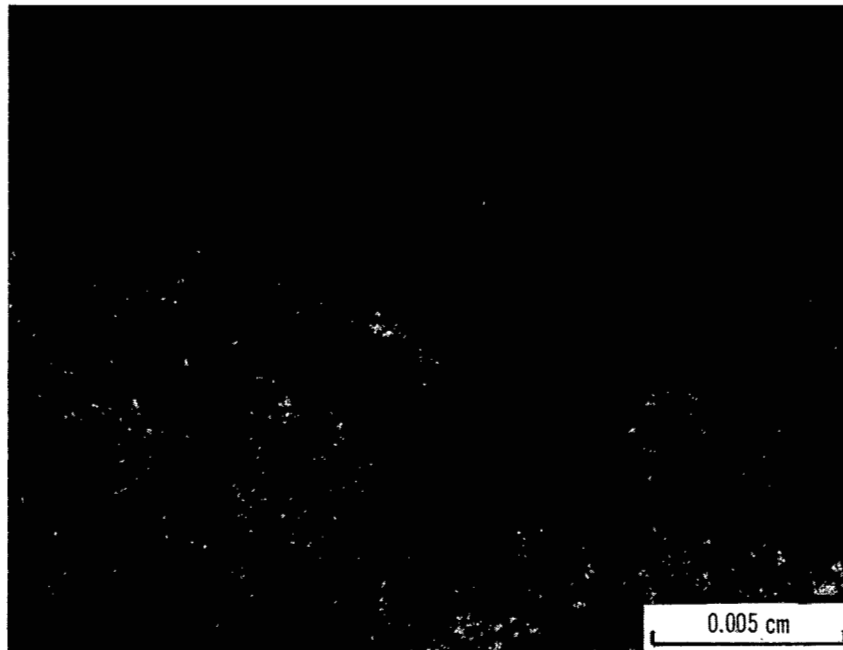


(a) Case microstructure; picral etch.

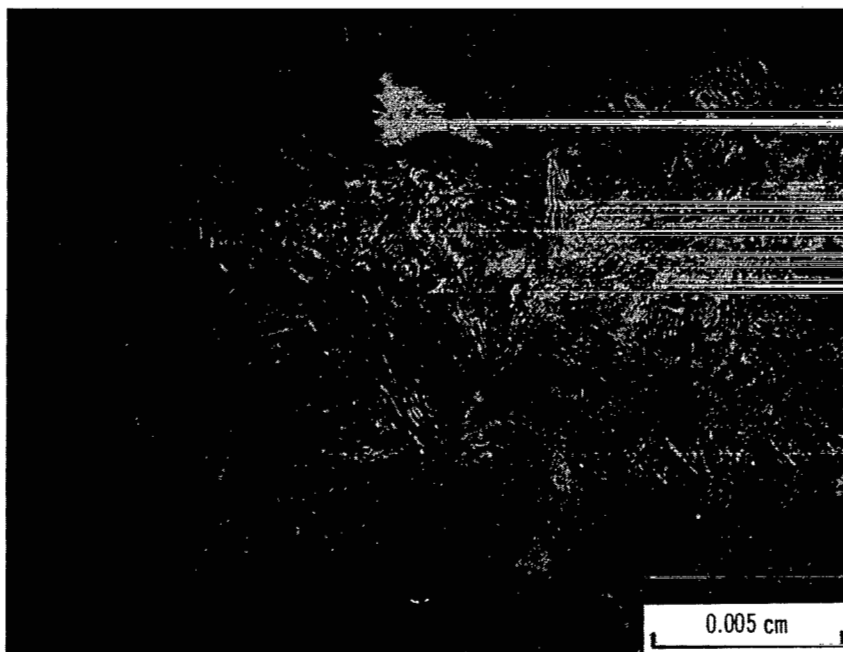


(b) Core microstructure; picral etch.

Figure 9. - Abnormal optical microstructure of CBS 600, lot A.

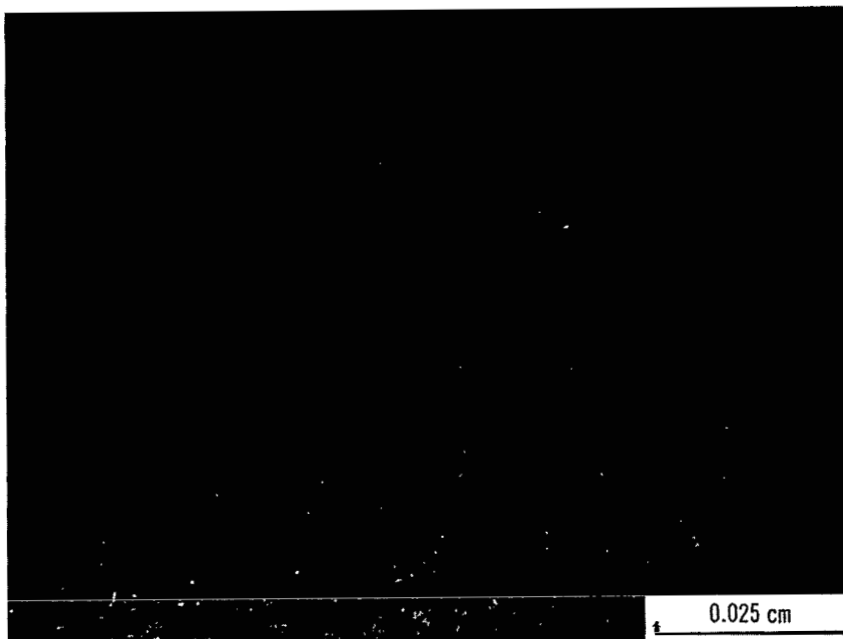


(c) Case microstructure; nital etch.

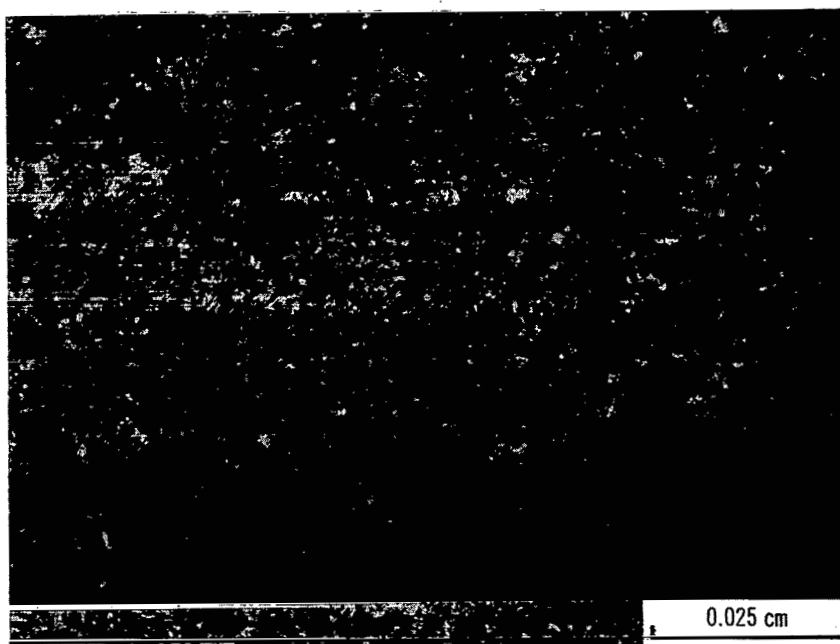


(d) Core microstructure; nital etch.

Figure 9. - Concluded.

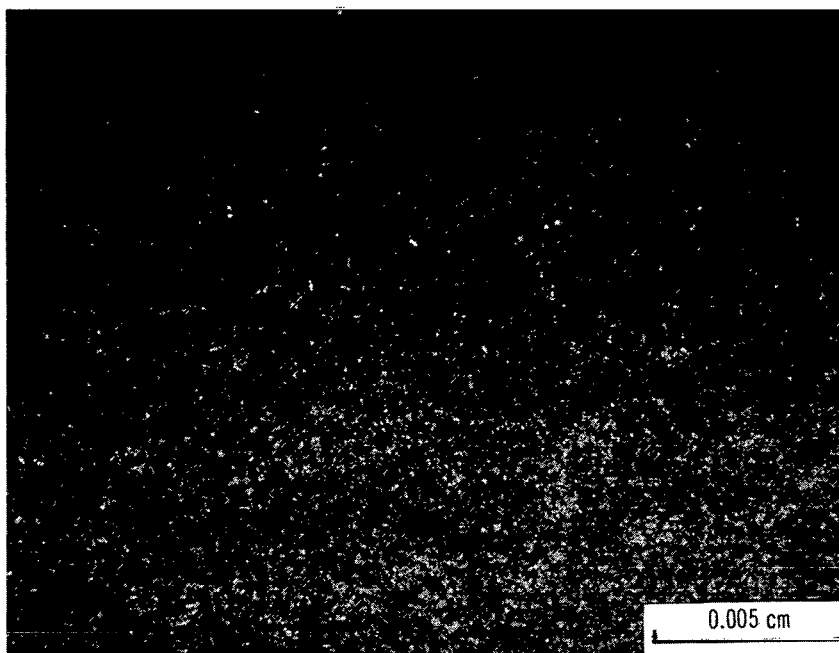


(a) Case microstructure; lot B; picral etch.

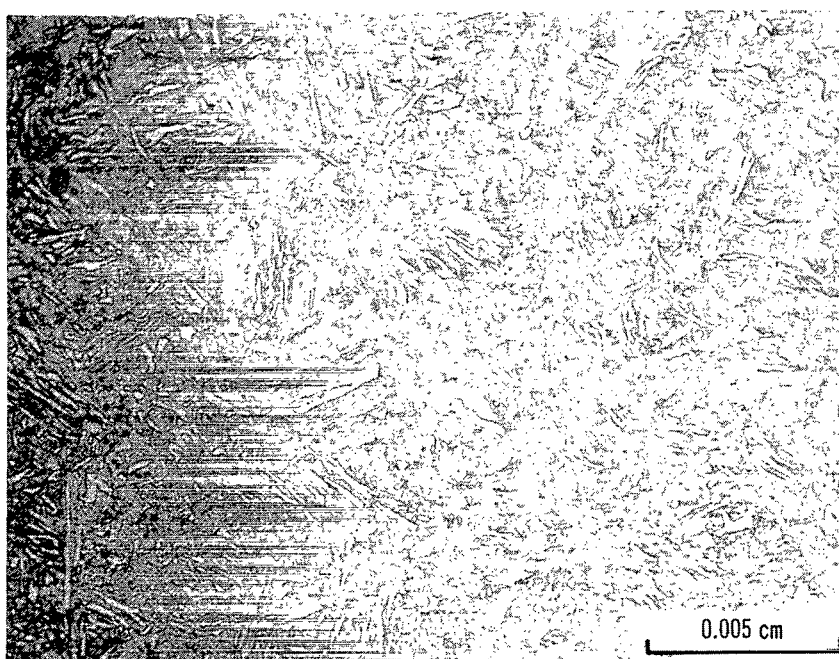


(b) Core microstructure; lot B; picral etch.

Figure 10. - Normal optical microstructure of CBS 600.



(c) Case microstructure; lot D; nital etch.



(d) Core microstructure; lot D; nital etch.

Figure 10. - Concluded.



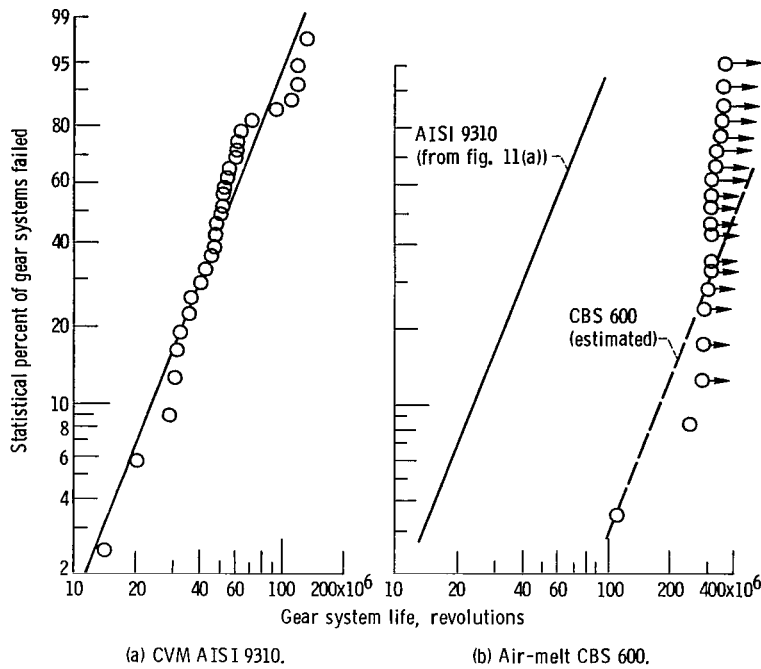


Figure 11. - Surface fatigue life of test gears. Speed, 10 000 rpm; maximum Hertz stress,  $1.71 \times 10^9$  newtons per square meter (248 000 psi); temperature, 350 K (120° F); lubricant, synthetic paraffinic with 5 percent EP additive.

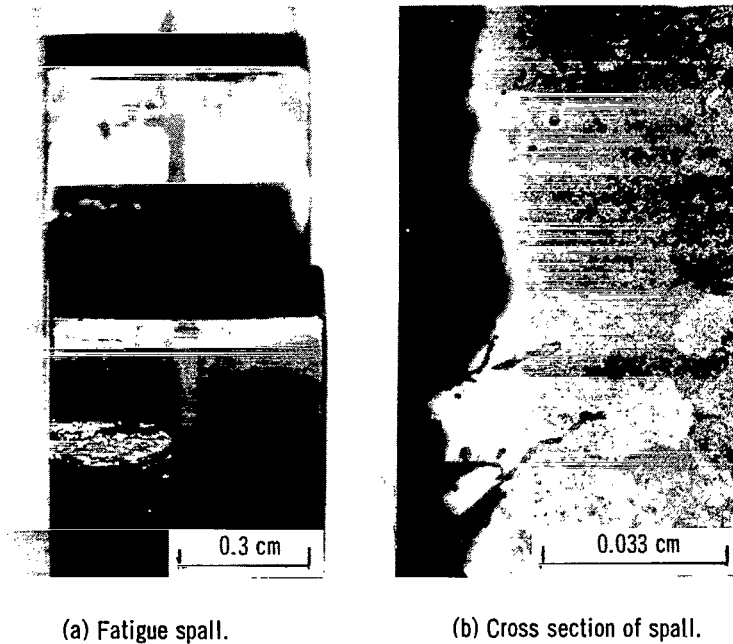
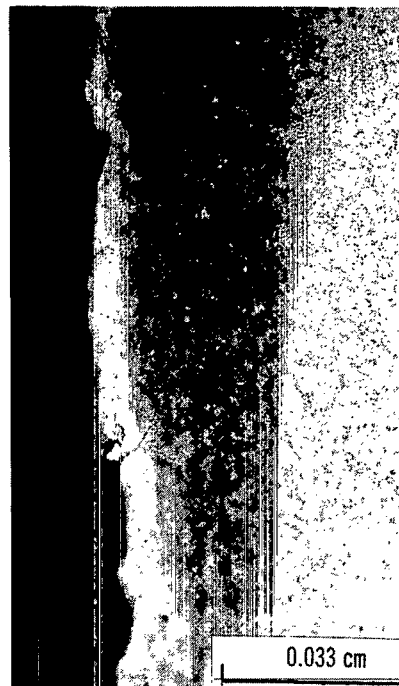


Figure 12. - Representative fatigue spall of test gear material CVM AISI 9310 steel. Speed, 10 000 rpm; lubricant, synthetic paraffinic oil with additive package.



(a) Fatigue spall.



(b) Cross section of spall.

Figure 13. - Typical pitch-line fatigue spall of CBS 600 test gear. Speed, 10 000 rpm; lubricant, synthetic paraffinic oil with additive package.

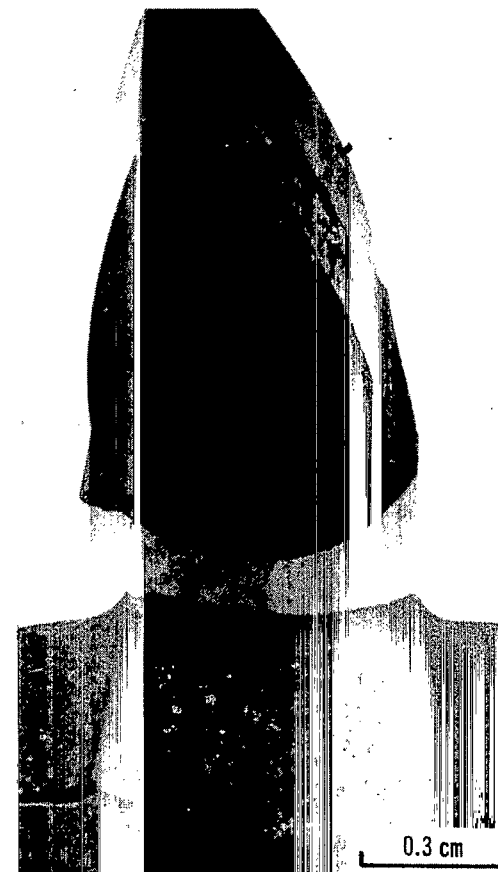


Figure 14. - Typical tooth bending fracture on CBS 600 after running with a fatigue spall; speed, 10 000 rpm; lubricant, synthetic paraffinic oil with additive package.

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16. Abstract Gear endurance tests were conducted with one lot of consumable-electrode vacuum-melted (CVM) AISI 9310 gears and one lot of air-melt CBS 600 gears. The gears were 8 pitch with a pitch diameter of 8.89 centimeters (3.5 in.). Bench-type rolling-element fatigue tests were also conducted with one lot of CVM AISI 9310, three lots of CVM CBS 600, and one lot of air-melt CBS 600 material. The rolling-element bars were 0.952 centimeter (0.375 in.) in diameter. The CBS 600 material exhibited pitting fatigue lives in both rolling-element specimens and gears at least equivalent to that of CVM AISI 9310. Tooth fracture failure occurred with the CBS 600 gears after overrunning a fatigue spall, but it did not occur with the CVM AISI 9310 gears. Tooth fracture in the CBS 600 was attributed to excessive carbon content in the case, excessive case depth, and a higher than normal core hardness.		
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